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Nonlinear Dynamics and Control of Large Arrays of Coupled Oscillators: Application to Fluid-Elastic Problems

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Introduction

Large numbers of fluid elastic structures are part of many power plant systems and vibration of these systems sometimes are responsible for plant shut downs. Earlier research at Cornell in this area had centered on nonlinear dynamics of fluid-elastic systems with low degrees of freedom. The focus of current research is the study of the dynamics of thousands of closely arrayed structures in a cross flow under both fluid and impact forces. This research is relevant to two areas:

a) First, fluid – structural problems continue to be important in the power industry, especially in heat exchange systems where up to thousands of pipe-like structures interact with a fluid medium. [Three years ago in Japan for example, there was a shut down of the Monju nuclear power plant due to a failure attributed to flow induced vibrations.]

b) The second area of relevance is to nonlinear systems and complexity phenomena; issues such as spatial temporal dynamics, localization and coherent patterns entropy meaasures as well as other complexity issues.

Early research on flow induced vibrations in tube row and array structures in cross flow goes back to Roberts in 1966 and Connors in 1970 . These studies used linear models as have many of the later work in the 1980's. Nonlinear studies of cross flow induced vibrations have been undertaken in the last decade. The research at Cornell sponsored by DOE has explored nonlinear phenomena in fluid-structure problems.

In the work at Cornell we have documented a subcritical Hopf bifurcation for flow around a single row of flexible tubes and have developed an analytical model based on nonlinear system identification techniques. (Thothadri, 1998, Thothadri and Moon, 1998,

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1999). These techniques have been applied to a wind tunnel experiment with a row of seven cylinders in a cross flow. These system identification methods have been used to calculate fluid force models that have replicated certain quantitative vibration limit cycle behavior of the vibrating cylinders. The methods are based on nonlinear analysis ideas such as harmonic balance and center manifold theory.

In a set of new experiments we have looked at the dynamics of 300 and 1000 vibrating rods in cross flow. (See Moon and Kuroda references below.) Classic fluid structure experiments have generally taken a reductionist view of fluid-elastic dynamics, namely one attempts to measure or derive force-flow relations for a single structure and then extend the results to a large number of structures. However in strongly non-linear systems such reductionist analysis does not always capture important phenomena such a chaotic dynamics, localization and coherent structures. In the case of large numbers of closely packed structures in a fluid flow, strong nonlinear effects include impact between structures. Also in large arrays, there is a natural random deviation from an exact periodic pattern that may affect the global spatial and temporal dynamics. Another complexity is the time delay effect of upstream eddies from vibrating structures driving downstream structures.

Experimental Results

In experiments in 2000, we studied 300 cantilevered steel rods in cross flow undergoing mutual impact between rods, we have observed complex, wave-like patterns as well as turbulent behavior in the rod array. The dynamic pattern seems to change from random-like behavior of the rods under turbulent buffeting for low velocities and more organized, wave-like behavior as the rods begin to impact one another.

The tunnel used had a working cross section of 25.6 cm by 25.6 cm and a maximum wind speed of 12 m/sec. The rod diameter was 1.59 mm and the length was 17.1 mm. The Reynold's number based on rod diameter was varied from 200 – 900.

Video time sequence pictures of the rod dynamics were taken. The latter reveal moving clusters of rods in time which appear similar to waves of rod clusters as the intensity of the impacts increases.

The impact time history from an accelerometer mounted at the base of one of the rods in the last row was also measured. The accelerometer was mounted at the base so that the low frequency modes were filtered out and only the high frequency modes due to impact between rods were excited. The impact rate versus flow velocity reveals a possible scaling relation between flow velocity and impact frequency. The critical velocity is close to 5.6 m/sec and is the velocity at which a significant number of rods begin to impact each other.

In previous work we have developed linear and nonlinear force models based on experimental measurements (Thothadri and Moon, 1998,1999). However those models did not include impact forces between rods. For *thousands of rods* however, it is near impossible to model the hit or miss dynamics of impacting rods. In one attempt to develop a so-called proto-model to capture the rod impact, we are using exponential *Toda potentials* which have been used to model atomic forces. Another theoretical avenue is to develop a *mixture theory model* or *two-phase continuum models* based on ideas of kinetic theory. We have been working with Professor James Jenkins of Cornell who has developed similar theoretical models for granular media.

In 2001, we increased the number of rods from 300 to 1000. We have been able to accomplish the following goals;

i) High speed video and post video image processing
ii) Selected motion sensor measurements on a small array of rods
iii) Accelerometer motion and impact sensing on one and two rods on the array perimeter.

The results of these experiments on 1000 rods in cross-flow exhibit dramatic digital video images of collective nonlinear dynamics of vibrating and impacting rods in the flow. The results also show two main collective nonlinear modes in the array of both a symmetric and anti-symmetric spatial patterns. The results show again a critical flow velocity for large scale impact and the emergence of global modal behavior.

Conclusion

The results of this research have made two major contributions to the field of fluid-structure dynamics.

1) We have developed a nonlinear system identification methodology for identifying nonlinear force models in fluid elastic systems that can be extended to other nonlinear systems (See the references of Thothadri et al.)

2) We have designed a new set of experiments with a 1000 impacting rods in cross flow that exhibits emergent global behavior of the fluid structure array.

Japan-MITI Collaboration

Research on the experiments of 300 and 1000 rods in cross flow has received partial support from the Japanese Ministry of Trade an Industry, Mechanical Engineering Division, through the visit of Masaharu Kuroda, research engineer, during a 16 month period. Mr. Kuroda helped design and carried out the experiments reported in Moon and Kuroda (2001) and also built an experiment with 1000 polycarbonate rods in cross flow. After returning to Japan last year, Mr. Kuroda has continued to conduct research on the development of mathematical models based on the experimental data from the Cornell wind tunnel experiments.

Research Personnel:

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Graduate Research Assistant . Mani Thothadri. Completed Ph.D. 1999.

Masaharu Kuroda: Research Engineer, MITI, Mechanical Engineering Laboratory, Tsukuba, Japan. Visiting researcher, Cornell University. 2000-2001
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Publications related to this grant

Kuroda, M. and Moon, F.C., (2002) "Local Complexity and Global Modes in Large Arrays of Fluid-Elastic Oscillators", Proc. IMECE, (ASME) 5th Fluid Structure Interactions Symposium, Nov 17-22, 2002, New Orleans.

Moon, F.C. and Kuroda, M. (2001), "Spatio-Temporal Dynamics in Large Arrays of Fluid-Elastic, Toda-Type Oscillators", Sept. 2001, Physics Letters A.

Moon, F.C. and Kuroda, M. (2000), "Complexity Measures in Large Arrays of Fluid Elastic Oscillators" Presented at the *International Congress of Theoretical and Applied Mechanics*, Chicago, August 27 - Sept 1, 2000.

Moon, F.C. and Kuraoda, M. "Complex Dynamics in Large Arrays of Fluid-Elastic Oscillators"Proc. 18th Symposium on Energy Engineering Sciences, Argonne National Laboratory, May 15-16,2000 pp130-136.

Thothadri, M., Casa,R., D'Andrea, M. and Moon, F.C. Johnson, R. (2002) "Nonlinear System Identification of Multi- Degree of Freedom Systems" to Appear in *Nonlinear Dynamics*.

Thothadri, M. (1999), *Nonlinear System Identification and Control of Fluid-Elastic Vibrations of a Cylinder Row using Bifurcation Theory* Doctoral Dissertation, Cornell University, January 1999.

Thothadri, M. and Moon, F.C. (1998) "Helical Wave Oscillations in a Row of Cylinders in a Cross-Flow" *J. Fluids and Structures 12*, 591-613.

Thothadri, M. and Moon, F.C. (1999) An Investigation of Nonlinear Models for a Cylinder Row in a Cross Flow" *J. Pressure Vessel Technology*, ASME *121*, 133-141.